Jet Propulsion Laboratory
California Institute of Technology

Understanding the Impacts of Dynamic Drivers on Global Storm-time Ionosphere-Thermosphere (IT) System

Team:

PI: Olga Verkhoglyadova (JPL);

Co-Is: Dogacan Ozturk, Xing Meng (JPL); Joshua Semeter (Boston University);

Collaborators: Roger Varney, Ashton Reimer (SRI), Michael Hartinger (SSI), Stephen Kaeppler (Clemson University), Gang Lu (UCAR)

The primary **science goal** of the proposed research is to quantify distinct effects on global IT dynamics caused by magnetosphere-ionosphere wave coupling and variable electric fields.

Prior research:

Impact of improving resolution of high-latitude E (Codrescu et al., 1995; Crowley and Hackert, 2001; Deng and Ridley, 2007; Matsuo and Richmond, 2008; Deng et al., 2009; Cosgrove et al., 2009; 2011; Matsuo and Richmond, 2008; Cousins et al., 2013)

Modeling of dynamic IT response: Ridley et al., 1998; Lu et al., 2001, 2002; Connor et al., 2016

Theoretical analysis: Lysak, 1999; "inductive coupling" Lotko, 2004; Lysak, 2004; Lysak and Song, 2006; Lotko, 2007; Yoshikawa et al., 2010, 2011; Lysak et al., 2013; Lotko and Zhang, 2016; Verkhoglyadova et al., 2018; Lotko et al., 2018

Jet Propulsion Laboratory
California Institute of Technology

The primary **science goal** of the proposed research is to quantify distinct effects on global IT dynamics caused by magnetosphere-ionosphere wave coupling and variable electric fields.

DC (Direct Current) paradigm:

- Driving of high-latitude electrodynamics is generally described by an evolving set of quasi-steady-state electrostatic processes.
- Empirically determined drivers are based on statistical averages.
- This approach applies to processes at temporal scales larger than ~1000s (16 min) and spatial scales larger than ~500 - 1000 km (Richmond, 2010).

AC paradigm:

- Include variable and mesoscale E fields (boundary conditions for models) to capture high-latitude IT dynamics in intense storms.
- **Incorporate dynamic MIT coupling**, include MHD wave processes
- Represent localized and dynamic energy input

Jet Propulsion Laboratory
California Institute of Technology

Our proposed effort addresses the following objectives:

Objective 1. *Quantify dynamic IT driving using FAST and ISR measurements.*

- utilize ISR measurements to estimate regional ionospheric parameters and horizontal electric fields.
- construct empirical model of electric field variability based on analysis of high-resolution FAST data The target time scales of the driver variability: seconds to several minutes, the spatial scales: several kilometers to hundreds kilometers.

Objective 2. *Adapt GITM to dynamical driving by wave field inputs.* We will build upon existing theoretical studies and develop a general dynamic approach to be incorporated in GCMs: use of ISR measurements as the driver for high-latitude ionosphere, semi-analytical approaches with Alfvén waves.

Objective 3. *Quantify impacts on global and regional IT caused by dynamic MI coupling in intense storms.* Case studies, analysis and validation of GITM output, comparison with ground-based and satellite data (GPS TEC, TIMED, etc.).

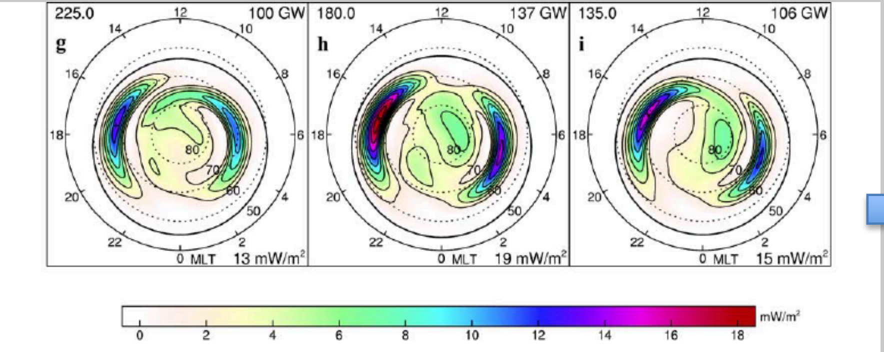
Objective 4. *Determine energy budget of dynamically driven IT system.* We will revise and extend the definition of energy budget of the IT system by including AC processes into high-latitude electrodynamics, validate it and outline implementation into a GCM.

Jet Propulsion Laboratory
California Institute of Technology

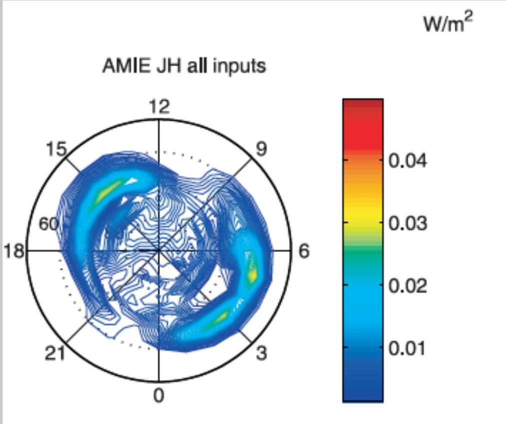
First steps:

- ✓ Perform theoretical analysis of Alfvén wave energy deposition in the IT, provide first analytical estimates
- ✓ Quantify dynamic electric field drivers using PFISR measurements for *the Isinglass* experiment interval
- ✓ Design and perform high-resolution GITM runs with dynamic inputs for selected events
- ✓ Start validation and comparison of the modeling results with diverse observations
- Establish a framework for error budget and uncertainty estimates

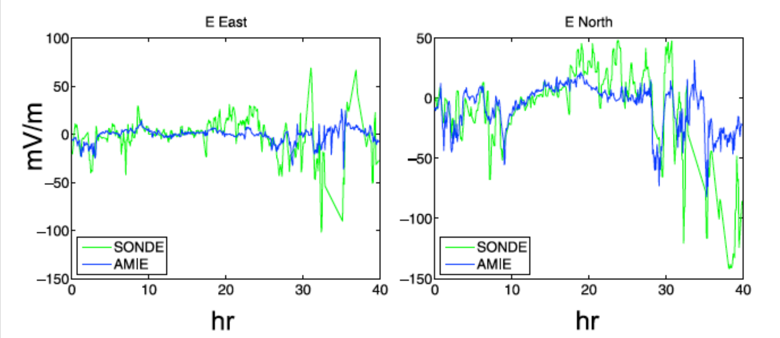
Joule heating at mesoscale



Empirical model at 110 km altitude
(*Weimer, JGR, 2005*)



AMIE reconstruction of Joule heating for 11:10 UT on 15 May 1997 (*McHarg et al., 2005*)



Eastward and northward E components measured by Sondrestrom (green) and modeled by AMIE (blue) starting 9 Jan 1997 (*Cosgrove et al., 2009*)

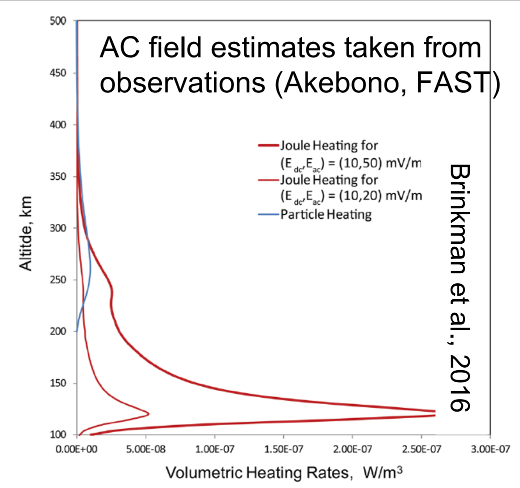
Jet Propulsion Laboratory
California Institute of Technology

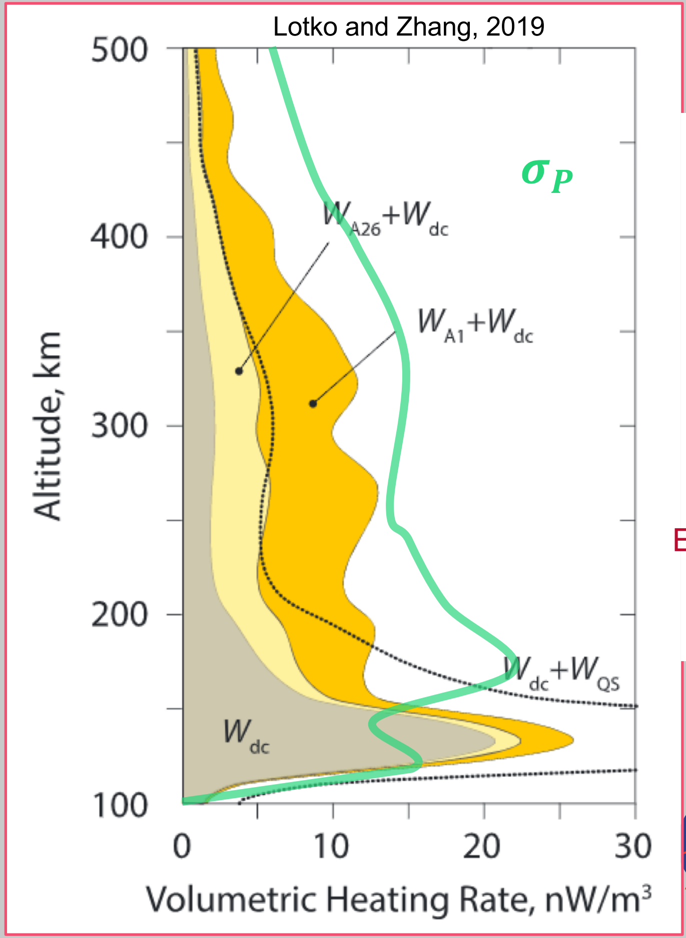
✓ ***JH estimation depends on spatial and temporal resolutions of the method***

Wave contribution to the I-T Energy Budget

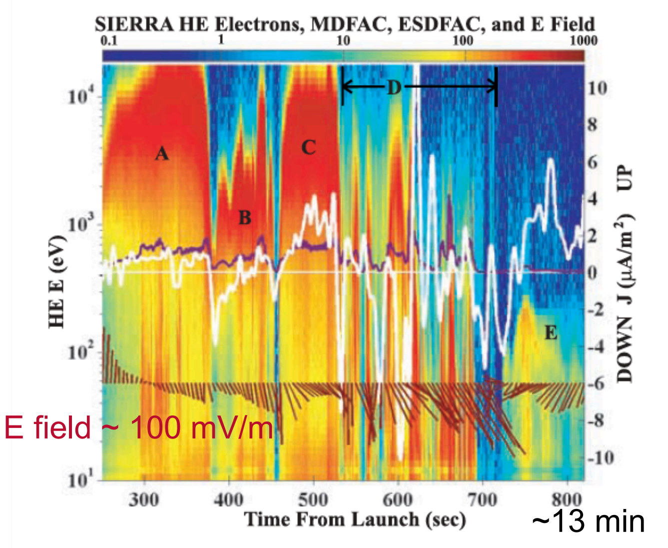
Heating by Alfvén waves

depending on the frequency range and propagation mode (Verkhoglyadova et al., 2018; Lotko et al., 2018)





NASA SIERRA rocket mission (Klatt et al., 2005)



14 January 2002 above PFISR (<735 km), differential electron flux (left axis) and FAC structures (right axis)

Jet Propulsion Laboratory
California Institute of Technology

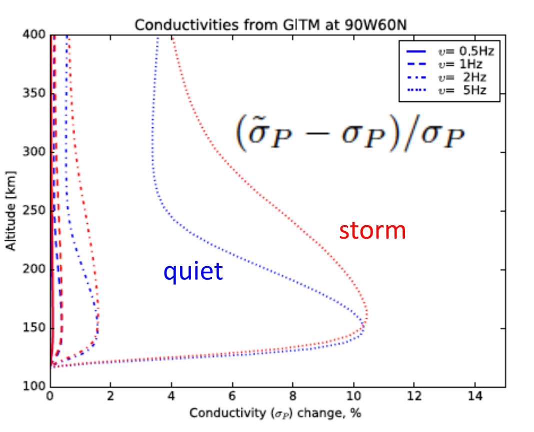
The relative efficiencies of Alfvén wave dissipation during quiet-time and storm

$$\langle\frac{\partial W}{\partial t}\rangle_T = \tilde{\sigma}_P\langle|E_\perp|^2\rangle_T$$

$$\tilde{\sigma}_P = \epsilon_0 \sum_\alpha \frac{\nu_\alpha \omega_{p\alpha}^2 (q_\alpha^2 + 2\omega^2)}{q_\alpha^4 + 4\omega^2\nu_\alpha^2}, \quad \tilde{\sigma}_{||} = \epsilon_0 \sum_\alpha \frac{\nu_\alpha \omega_{p\alpha}^2}{\omega^2 + \nu_\alpha^2},$$
$$q_\alpha^2 = \nu_\alpha^2 - \omega^2 + \omega_{c\alpha}^2.$$

GITM modeling of the 13-14 October 2016 storm

Changes in the Pedersen conductivity due to waves at 60° lat and 12LT



$$\kappa = \frac{Q_w}{Q_s} = \frac{\tilde{\sigma}_P}{\sigma_P} \cdot \frac{\langle|E_{\perp w}|^2\rangle_T}{|E_{\perp s}|^2} \approx 1.1 \cdot \frac{\langle|E_{\perp w}|^2\rangle_T}{|E_{\perp s}|^2}$$

$E_{\perp s}$ quasi-static field

Table 1. Horizontal electric field estimations from GITM at 60° latitude.

Time	Quiet time value, mV/m	Storm time value, mV/m
12 LT (18 UT)	0.25 (11 Oct.)	46 (13 Oct.)
20 LT (06 UT)	0.60 (12 Oct.)	30 (14 Oct.)

$E_{\perp w} \sim 20 - 40\ mV/m$ Alfvén wave field

Alfvén wave contribution to storm energy deposition as compared to static Joule heating:

$\kappa \approx 30\ \%$

- An analytical expression for energy deposition by propagating Alfvén waves in the collisional ionosphere-thermosphere is derived.
- The relative efficiency of energy deposition rate of Alfvén wave (up to 5Hz in. frequency) to static field is estimated to be ~10% at high latitudes and below 250 km altitude.
- We show that Alfvén wave energy deposition can reach about 30% of the value of static Joule heating during a strong storm.
- This effect carries important implications for ionospheric dynamics, especially for density enhancement in the daytime cusp, heating in the vicinity of auroral arcs and ion outflow.

Jet Propulsion Laboratory
California Institute of Technology

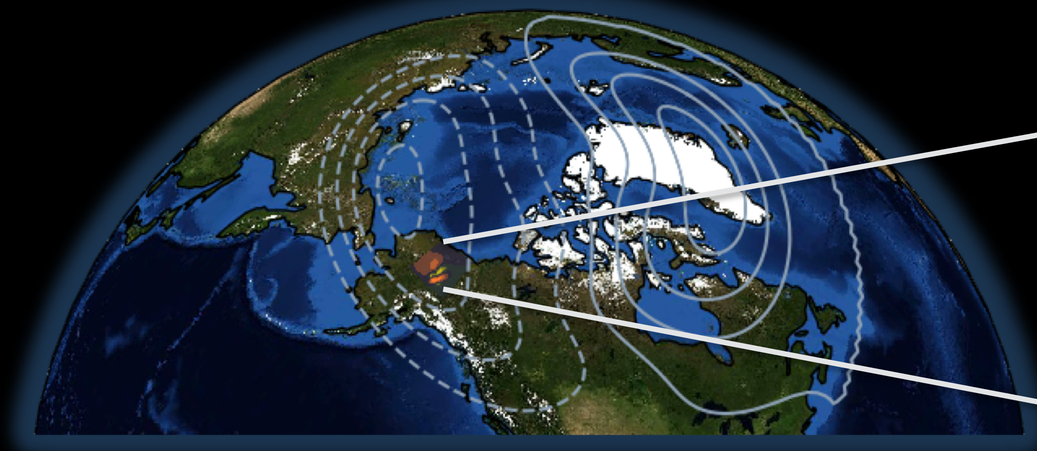
Verkhoglyadova et al, JGR, 2018; https://doi.org/10.1029/2017JA025097.

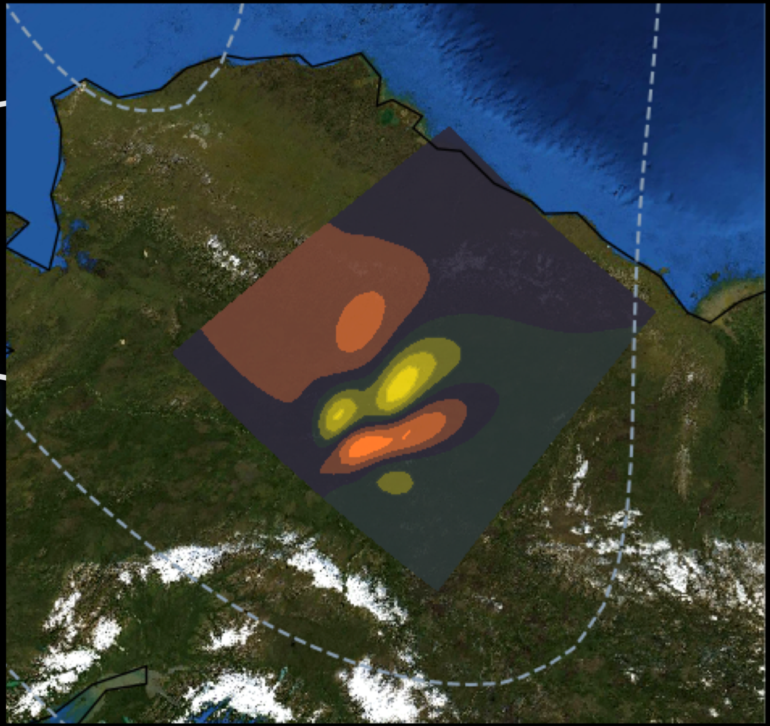
Suggested collaboration topics:

- Effects of different temporal and spatial scales in high-latitude and low-latitude IT electrodynamics:
    - What are the characteristic scales of electrodynamic processes? Are there principal distinctions between large-scale (>500km) and mesoscale (~200-500 km in horizontal scale) processes?
    - Is there a dependence of differences between observations and modeling results on a scale?
- Improved characterization of ionospheric conductivity
- Quantification of energy input and deposition (Joule heating) in the high-latitude IT at multi-scales

Data sharing:

- AMIE model output for better specification of GITM driving for several case studies
- Global Ionospheric Maps (GIM) for selected dates: global TEC snapshot every 15 min





Understanding the Impacts of Dynamic Drivers on I-T

Dogacan Su Ozturk

PI: Olga Verkhoglyadova (JPL)

Co-Is: Xing Meng (JPL); Joshua Semeter (Boston University);

Collaborators: Roger Varney, Ashton Reimer (SRI), Michael Hartinger (SSI),
Stephen Kaeppler (Clemson University), Gang Lu (UCAR)

Jet Propulsion Laboratory
California Institute of Technology

contact: dogacan.s.ozturk@jpl.nasa.gov

Key Questions and Objectives of the Study

Questions:

- What is the importance of meso-scale structures on I-T energy budget?
- What are the characteristics of meso-scale energy deposition?
- What role do meso-scale structures play in M-I-T coupling?

Objectives:

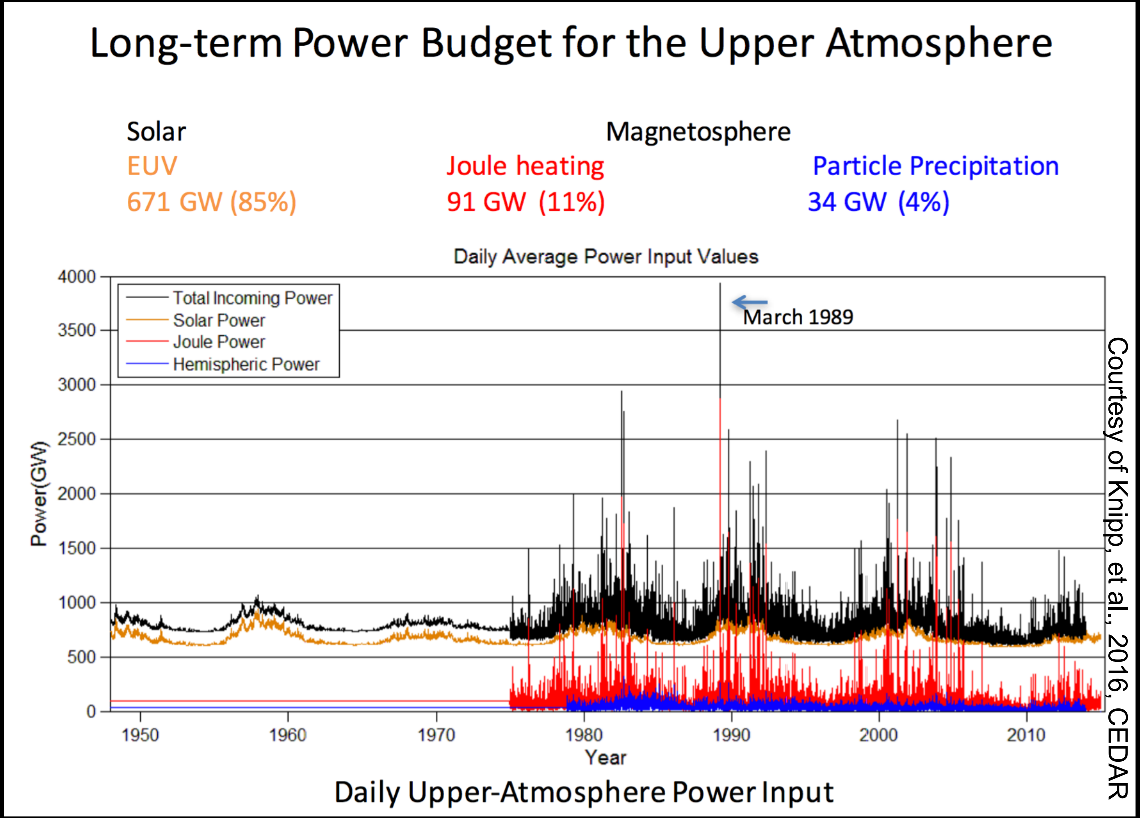
→ Quantify dynamic IT driving using ISR measurements

→ Adapt a first-principles model (GITM) to dynamical driving

→ Quantify impacts on the regional I-T system

Introduction I: Energy budget of the high-latitude I-T

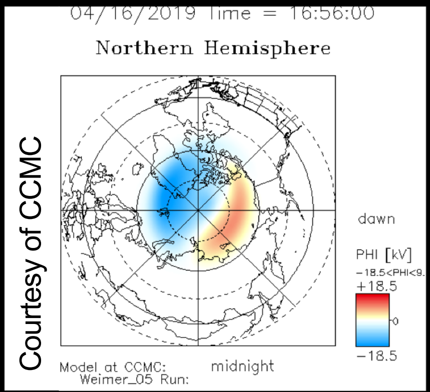
- Solar EUV is the dominant energy source for the I-T system.
- Joule heating ($\sigma_p E^2$) and particle precipitation are important during periods of high solar activity.



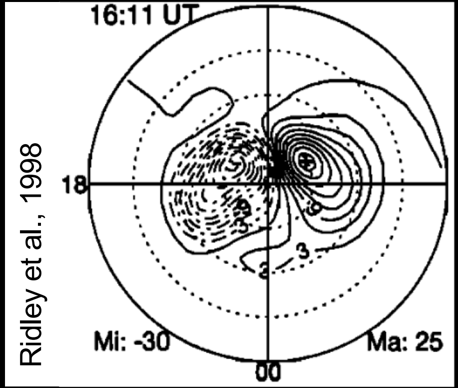
Electromagnetic energy from the magnetosphere (source) → Joule heating at the I-T (sink)

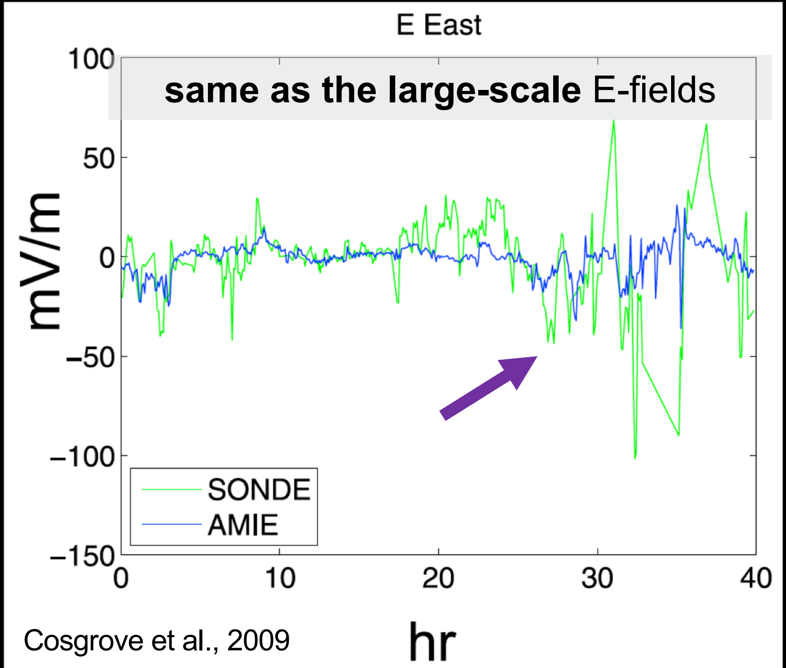
Introduction II: Estimating the Energy Transfer from Magnetosphere

Weimer Model :



AMIE Model:





Not resolving meso-scale electric field variability (temporal + spatial) → underestimated Joule Heating

- Traditionally, conductivity and electric fields are estimated through empirical models.
- Current models can not resolve the meso-scale structures but significant work is ongoing*.
- Dynamic (< 15 minutes), allows for wave solutions, **meso- (500-150 km)** and small-scale (<100 km)

*[Codrescu et al. 2008; Deng et al. 2009; Matsuo & Richmond 2008; Zhu et al. 2018].

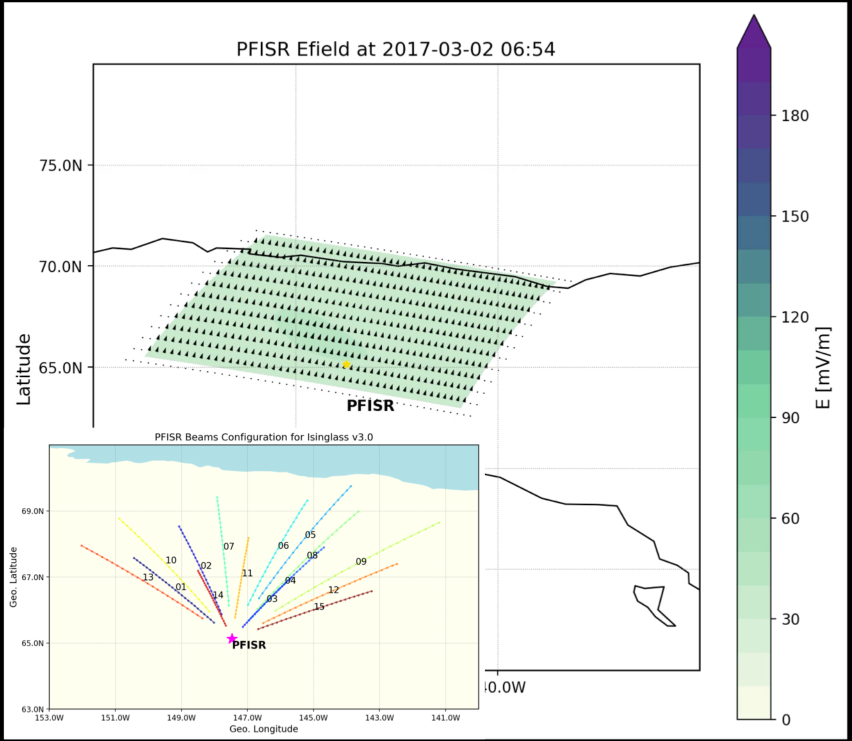
Problem I: A methodology to determine meso-scale driving does not exist.

PFISR LOS velocity measurements can be used to derive Electric fields on a 2D grid*.

→ The potential change in longitude (x) and latitude (y) can be calculated:

$$\Delta\phi_x = -\int_{x_1}^{x_2} E_x\, dx\,,\ \Delta\phi_y = -\int_{y_1}^{y_2} E_y\, dy$$

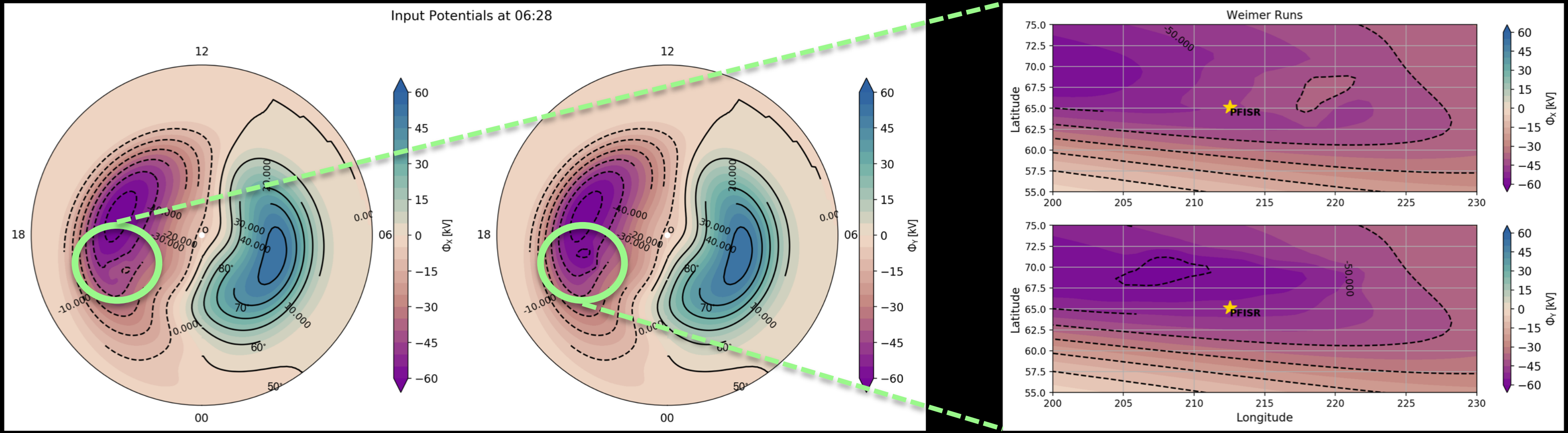
1. Down-sample the x and y components of the electric fields on desired grid. (0.75°x0.75°)
2. Calculate the potentials on the new grid to drive GITM.



* Procedure requires certain amount of beams, data courtesy of Roger Varney and Ashton Reimer.

Problem II: A global model can't run with only local specifications.

→ Merge the calculated potentials with Weimer potentials to obtain a global potential pattern.

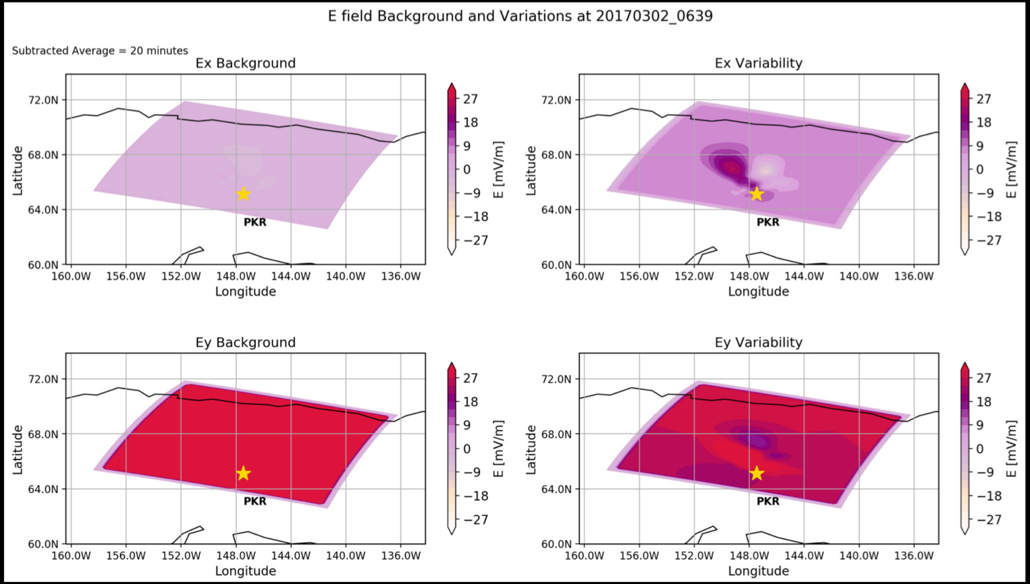


1. Constrained the problem with Weimer potentials
2. Use two potentials to preserve the features in PFISR measurements

Problem III: How to interpret and validate the model results?

→ Separate the PFISR measurements to background + variable electric fields

→ Calculate potentials and merge with Weimer potentials to drive GITM*



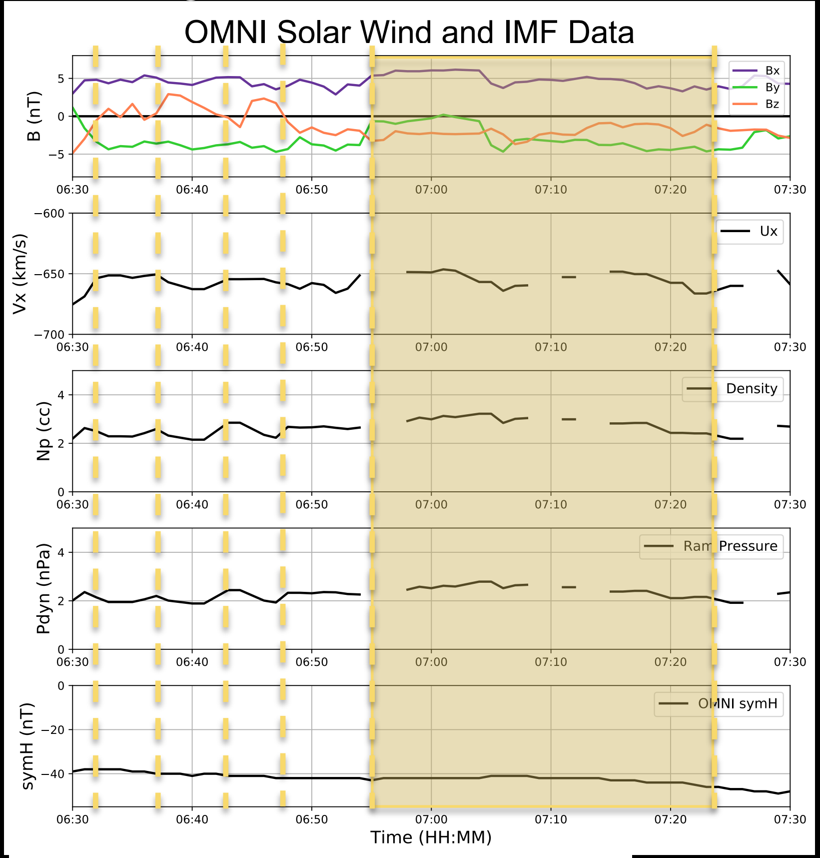
Comparisons of PFISR Ne, Te, and Ti measurements along the beams with

Simulations	Potentials
1	Weimer Electric Field Potentials
2	Measured Electric Field Potentials
3	Background Electric Field Potentials
4	Variable Electric Field Potentials

*The University of Michigan, Global Ionosphere Thermosphere Model (GITM) solves Navier-Stokes equations on 3D, altitude based non-uniform grid, assuming non-hydrostatic solution. [Ridley, Deng and Toth, JASTP, 2006]

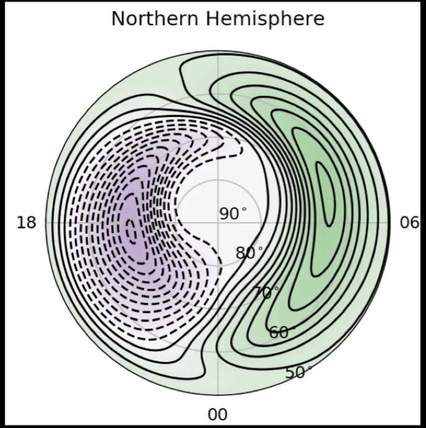
Results I: Sources of Meso-Scale Drivers

The large-scale drivers



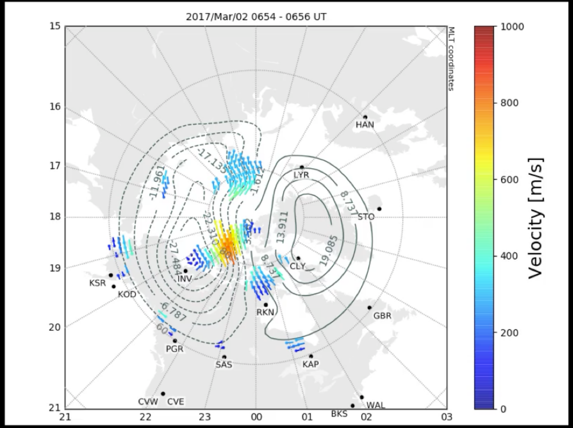
- Multiple IMF B_Z reversals
- High-speed solar wind
- Recovery phase

Weimer Potentials:



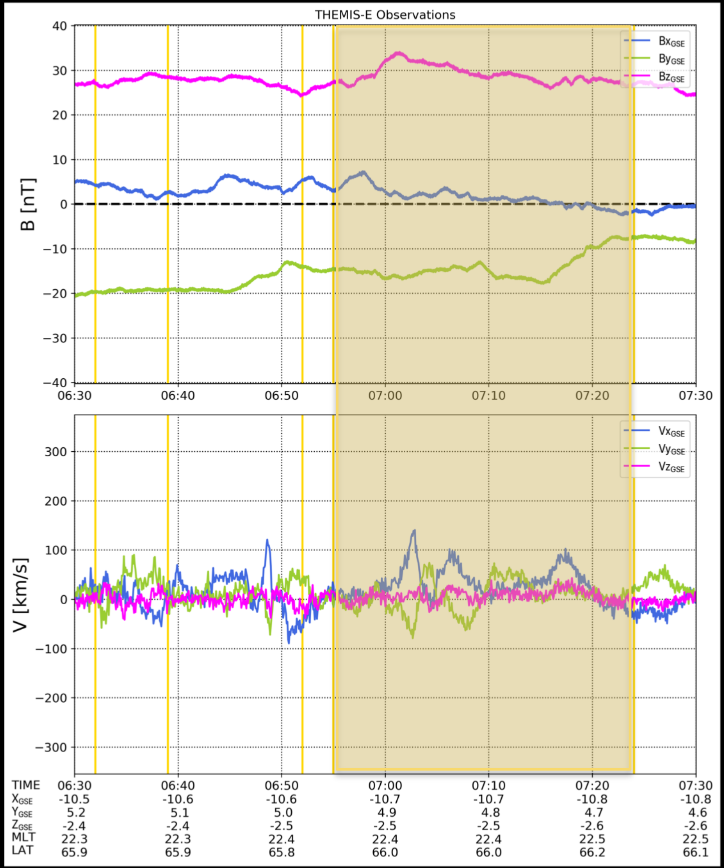
No significant response

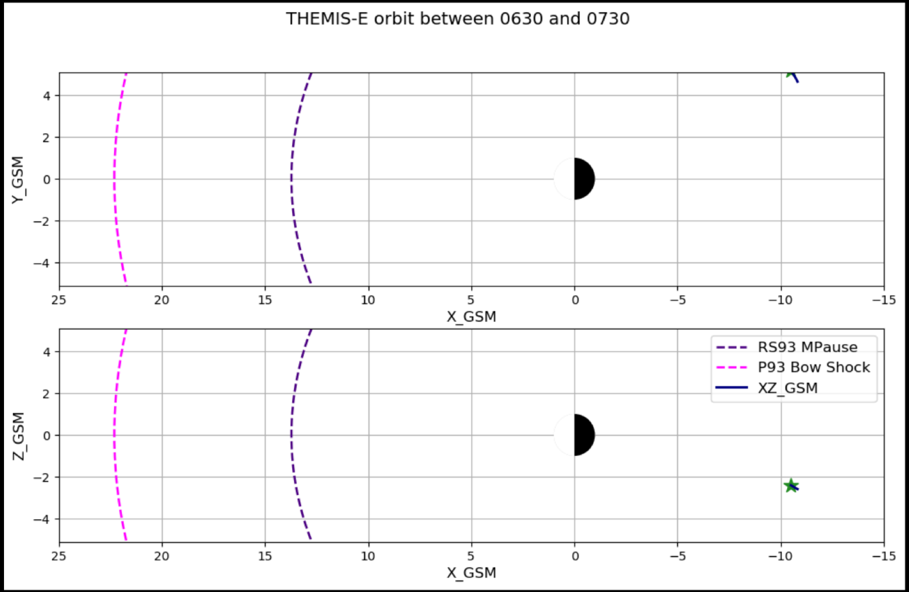
SuperDARN Potentials:



Flow enhancements

Results I: Sources of Meso-Scale Drivers



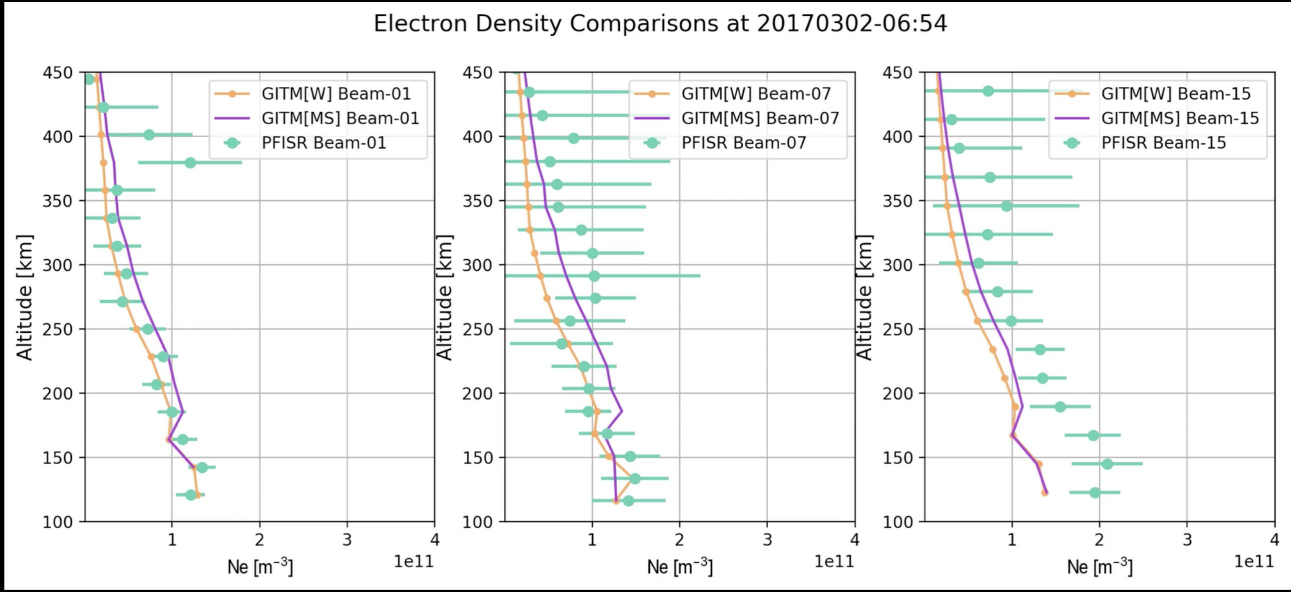


Themis-E recorded Earthward flow enhancements and slight B_Z reversals indicating possible magnetotail activity.

Results II: Effects of Meso-Scale Drivers

o Weimer simulations
o PFISR+Weimer simulations
o PFISR measurements

Electron density variation between 0655-0725 UT

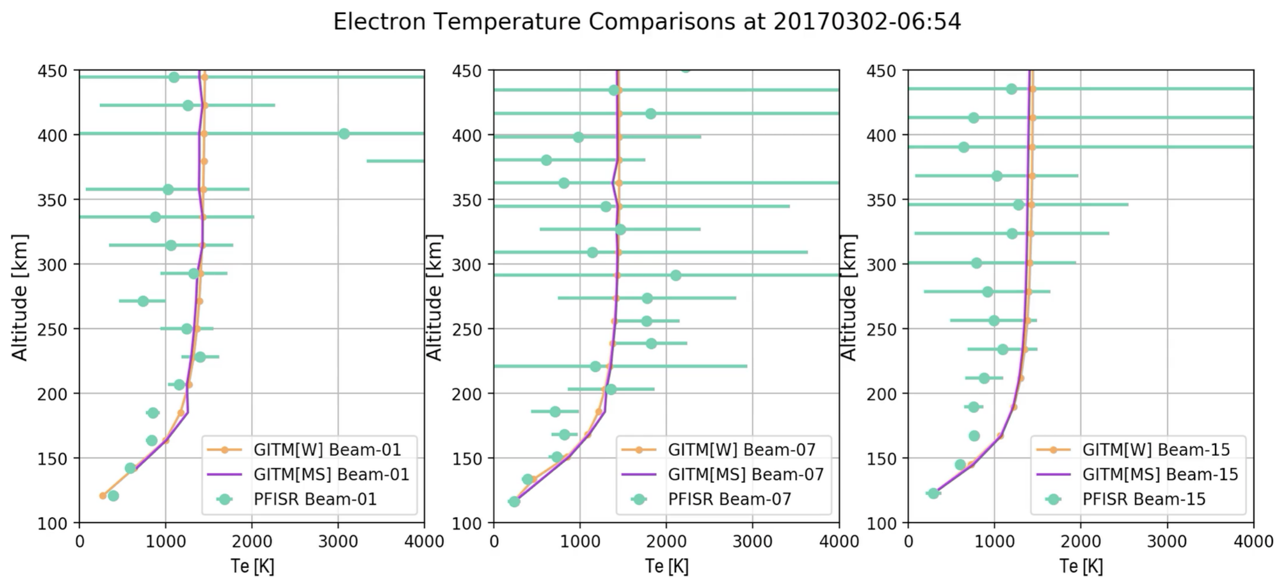


- Overall electron density increases compared to Weimer driven model.
- Measured enhancements around 150 km not captured well.
- Vertical profiles of measured electron densities are very dynamic.
- Meso-scale particle precipitation is not included.

Results II: Effects of Meso-Scale Drivers

Electron temperature variation between 0655-0725 UT

- o Weimer simulations
- o PFISR+Weimer simulations
- o PFISR measurements

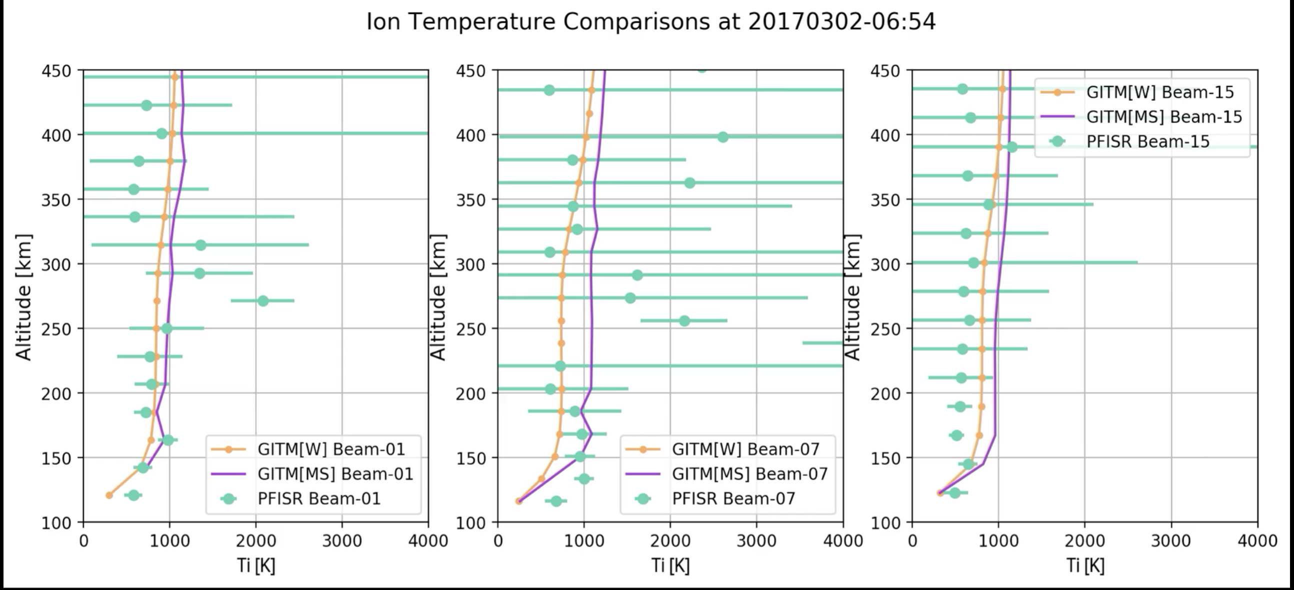


- Electron temperature is lower in the MS driven GITM simulations.
- Not enough cooling in electron temperature.
- No electron flux or energy input in meso-scale was included in the model.

Results II: Effects of Meso-Scale Drivers

Ion temperature variation between 0655-0725 UT

o Weimer simulations
o PFISR+Weimer simulations
o PFISR measurements



- Ion temperature is more sensitive to E field variability than electron temperature and density.
- More wave-like structures appear in the vertical profiles of ion temperature.
- Ion cooling mechanisms need improvement.

Summary

We have developed a framework that can utilize ISR measurements with a global I-T model to investigate the effects of meso-scale electric fields.

Objectives:

√ Quantify dynamic IT driving using ISR measurements

√ Adapt a first-principles model (GITM) to dynamical driving

√ Quantify impacts on the regional I-T system

Future work and Possible Collaboration

- Validation Studies:
  - Quantifying errors and uncertainties in the model
  - More event studies with different drivers (SuperDARN, AMIE), conjunction studies
- Wave Studies:
  - ULF wave studies to understand the AC drivers
  - Magnetospheric measurements

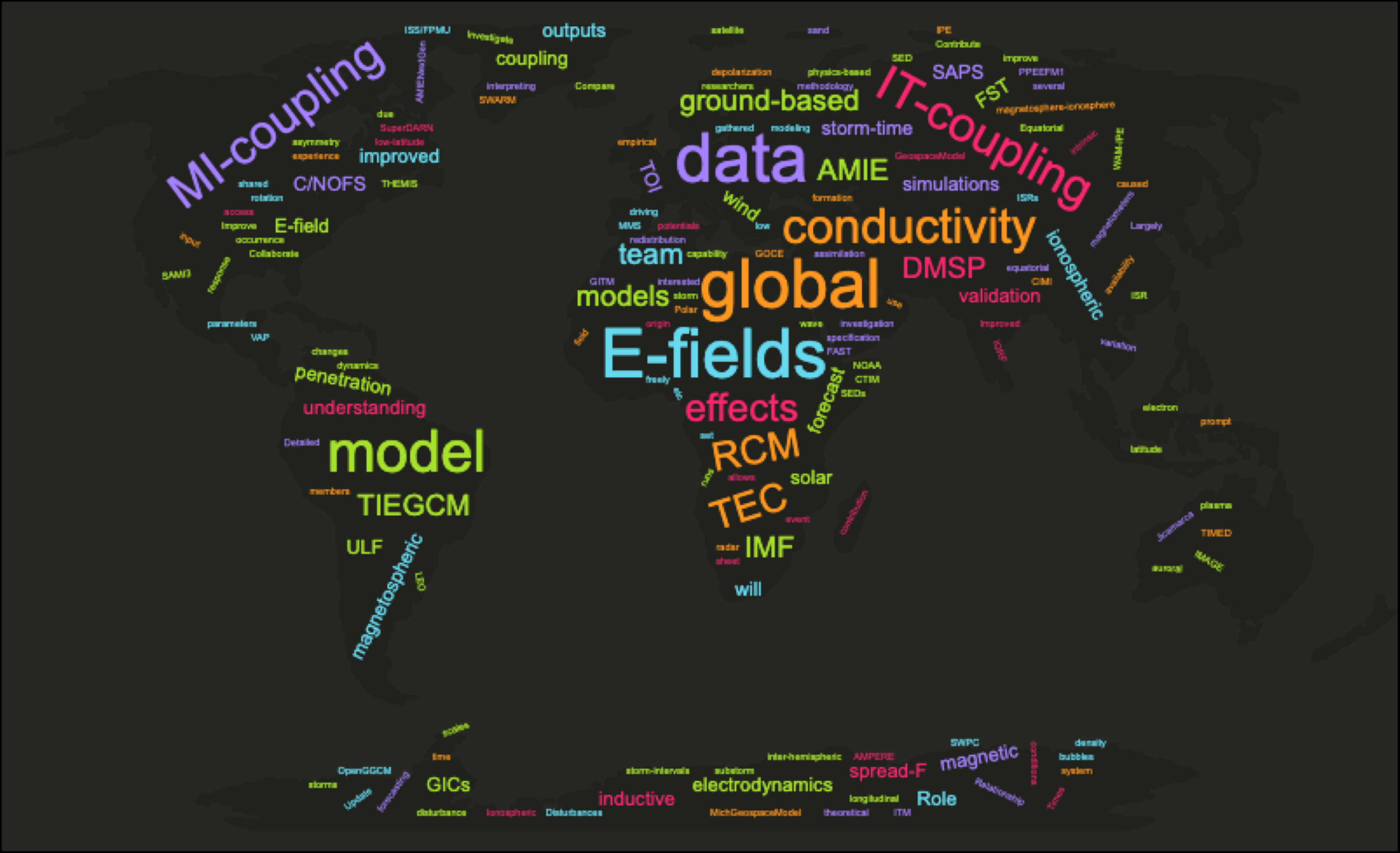
Questions:

- What is the importance of meso-scale structures on I-T energy budget?
- What are the characteristics of meso-scale energy deposition?
- What role do meso-scale structures play in M-I-T coupling?

Thank you.

Acknowledgements

- This work is funded by the NASA ROSES 2016 Heliophysics LWS Science (NRA NNH16ZDA001N) Program.
- GITM is developed and supported by Prof. Aaron Ridley at University of Michigan.
- Simulations were done on NASA High-End Computing Program through the NASA Advanced Supercomputing Division at Ames Research Center, and Stampede Supercomputer at Texas Advanced Computing Center at University of Texas at Austin.
- We acknowledge use of NASA/GSFC's Space Physics Data Facility's OMNIWeb (or CDAWeb or ftp) service, and OMNI data.
- We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS Mission. Specifically: C. W. Carlson and J. P. McFadden for use of ESA data; K. H. Glassmeier, U. Auster and W. Baumjohann for the use of FGM data provided under the lead of the Technical University of Braunschweig and with financial support through the German Ministry for Economy and Technology and the German Center for Aviation and Space (DLR) under contract 50 OC 0302.
- We acknowldge the use of the VT SuperDARN Web site (vt.superdarn.org) for access to radar data and data products. SuperDARN is a collection of radars funded by national scientific funding agencies of Australia, Canada, China, France, Italy, Japan, Norway, South Africa, United Kingdom and the United States of America.
- Simulation results have been provided by the Community Coordinated Modeling Center at Goddard Space Flight Center through their public Runs on Request system (http://ccmc.gsfc.nasa.gov). The Weimer Model was developed by Daniel R. Weimer at Virginia Tech. The Ovation Prime Model was developed by Patrick Newell at JHU/APL.



MI-coupling
IT-coupling
data
global
E-fields
conductivity
model
models
ground-based
effects
RCM
TEC
AMIE
DMSP
storm-time
simulations
SAPS
FST
TOI
team
validation
ionospheric
improved
C/NOFS
E-field
outputs
coupling
penetration
understanding
TIEGCM
ULF
magnetospheric
forecast
solar
IMF
will
wind
GICs
inductive
electrodynamics
spread-F
magnetic
Role
THEMIS
SuperDARN
ISS/FPMU
SWARM
AMPERE
OpenGGCM
MichGeospaceModel

Mutual theme: "Electric fields and conductivity across different scales"

Group #	1: JR	2: GL	3: SS	4: T-WF	5:OV	6:GC
TIEGCM		Uses				Uses
TEC	Validation	Validation		Validation	Validation/Can provide GIM	
RCM	Coupling		Coupling	Coupling		
Region	Global/high-lat	Global	Equatorial	Global/Equatorial	Global/high-lat.	Global
Data	Validation	Assimilation/ Validation	Validation	Validation	Assimilation/ Validation	Assimilation/ Validation
Conductivity	Can provide	Can provide	Can provide	Can provide	Can use	Can provide
MI Coupling	Investigates	Investigates	Investigates	Investigates	Investigates	Investigates
IT Coupling		Investigates		Investigates	Investigates	
AMIE		Uses AMIE		AMIENextGen	Can use	Uses AMIE
DMSP		Uses	Uses	Uses		Uses
IMF B_Y and B_Z	Investigates		Investigates			
Penetration Efields	Investigates		Investigates	Investigates		Investigates

Possible Simultaneous Collaborations

1. TIEGCM simulations
   – GL-GC
2. RCM simulations
   – JR-SS-TWF
3. Role of IMF orientation/magnitude
   – JR-SS
4. Role of penetration electric fields
   – JR-SS-TWF-GC
5. AMIE data assimilation
   – GL-TWF-GC

Possible Sequential Collaborations

1. OV can use AMIE results
2. JR, GL, TWF can use GIM-TEC data for validation
3. GC can use dB/dt estimates from TWF

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov